Controller Design for Enhanced Engine Response

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Contents

Motivation

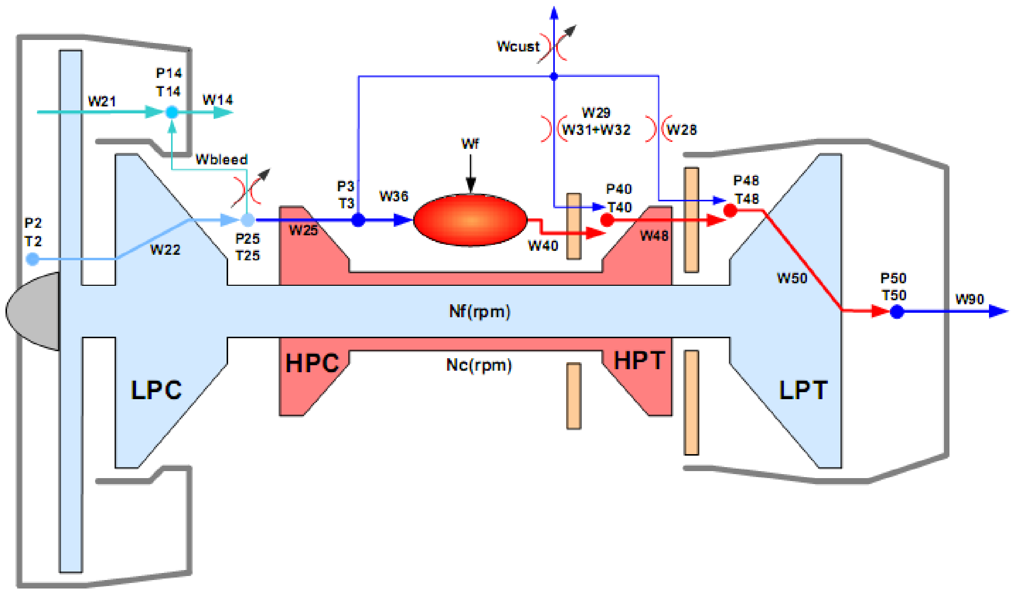
- Emergency situations (e.g. runway incursion, airframe damage, etc.) may warrant unconventional usage of aircraft engines
- Previous work:
  - Increased maximum thrust output (overthrust)
  - Enhanced dynamic thrust response
  - Enhanced engine performance and failure risk
  - Risk assessment: vehicle & engine risk balancing

- Litt et al., "A Risk Assessment Architecture for Enhanced Engine Operation," AIAA Infotech@Aerospace Conference, 2010.
- Csank et al., "Implementation of Enhanced Propulsion Control Modes for Emergency Flight Operation," AIAA Infotech@Aerospace Conference, 2011.
- McGlynn et al., "A Risk Management Architecture for Emergency Integrated Aircraft Control," AIAA Infotech@Aerospace Conference, 2011.
- Csank et al., "The Effect of Modified Control Limits on the Performance of a Generic Commercial Aircraft Engine," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2011.
- May et al., "Improving Engine Responsiveness during Approach through High Speed Idle Control," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2011.

Objective

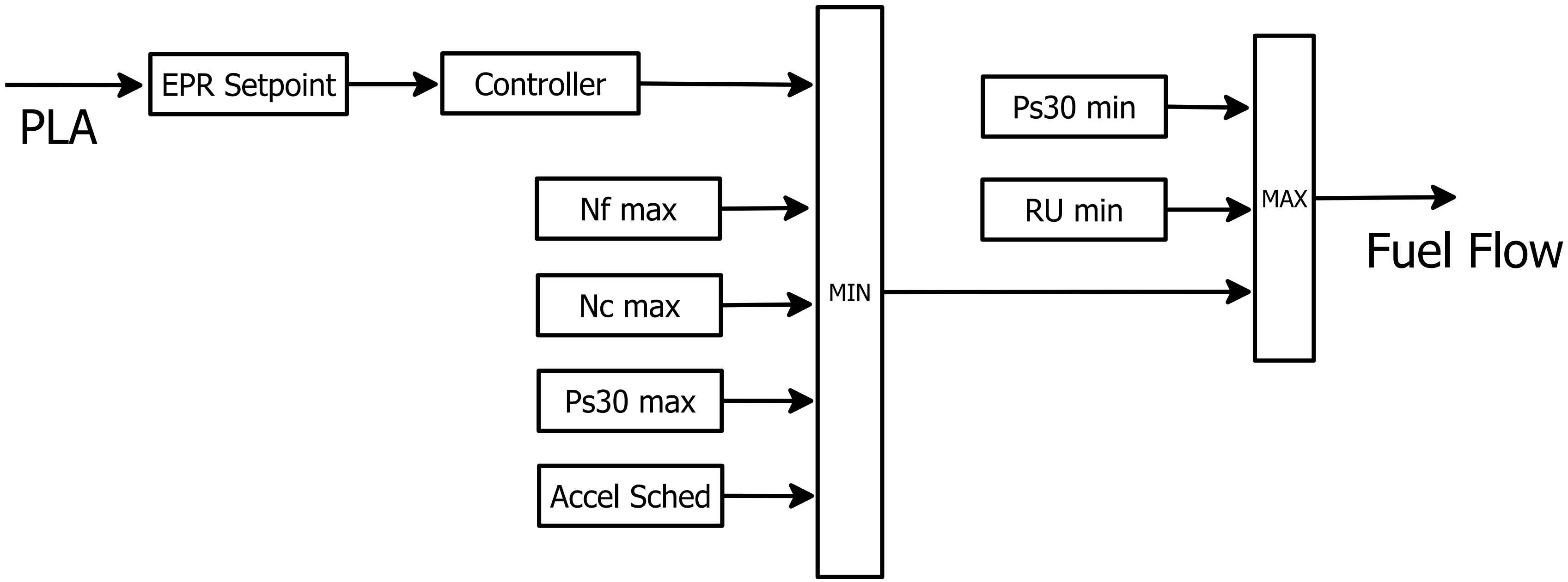
- Design control modes that provide enhanced performance based on consistent risk elevation
- Considerations:
  – Identify performance parameter(s) to be enhanced
  – Identify and characterize relevant engine failure or malfunction mode(s)
  – Designate allowable elevated probability of failure (i.e. vehicle/engine risk tradeoff)
- Develop performance-enhancing control logic
- Demonstrate on previously introduced concepts of overthrust and faster response using computer simulation of commercial-type turbofan engine

Simulation: C-MAPSS40k



- **C**ommercial **M**odular **A**ero-**P**ropulsion **S**ystem **S**imulation **40k**
- 40,000-lb thrust class, high-bypass, dual-spool turbofan engine
- Component performance maps
- Zero-dimensional, spool dynamics
- NASA Software Catalog (https://sr.grc.nasa.gov/)

Simulation: Control System



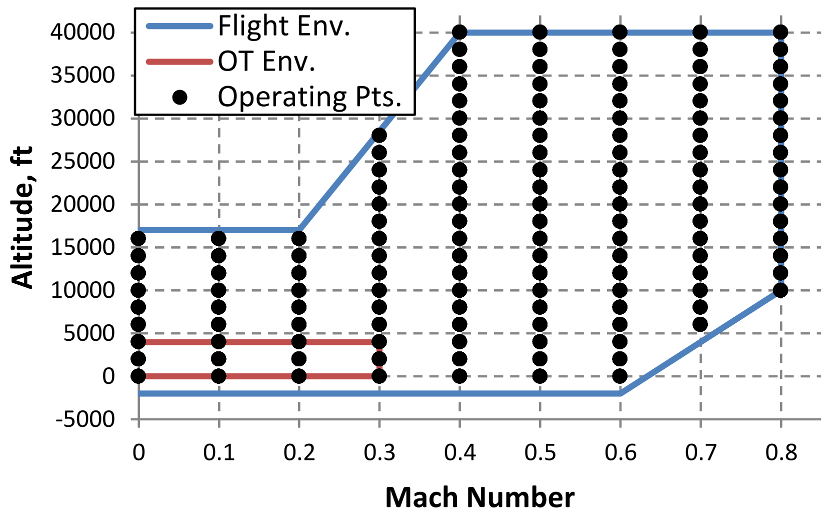
- Throttle command (PLA) provides setpoint for gain-scheduled PI feedback control on engine pressure ratio (EPR)
- Max/min regulators for limit protection

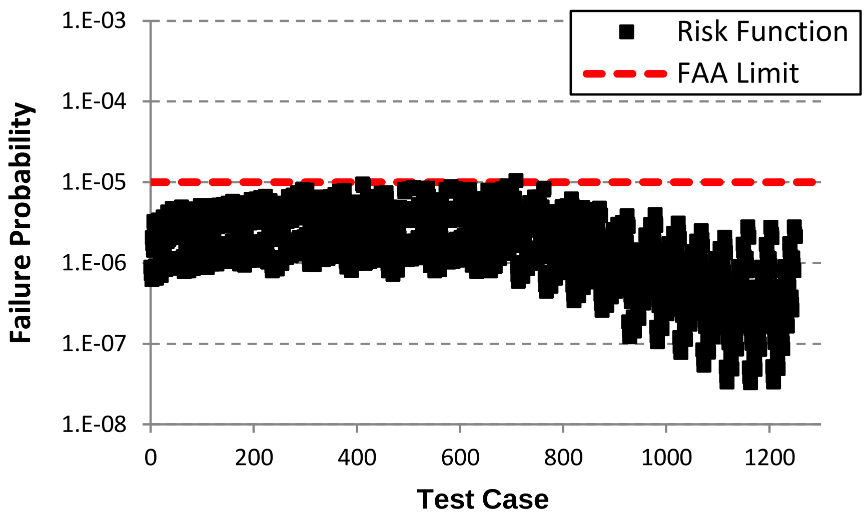
Overthrust: Design Considerations

- Increase engine thrust output beyond design maximum levels
- Risk: failure of disk or blade with contained debris
- FAA regulation on allowable rate of occurrence for contained failure types: 10^{-7} to 10^{-5} per flight hour (Aeronautics and Space, 14 C.F.R. pt. 33.75)
- Allowable elevated risk level for enhanced performance: 10^{-3} per flight hour

Overthrust: Risk Function

- Calculates risk of disk and blade failure as function of operating conditions
  - Fan speed (Nf)
  - Core speed (Nc)
  - HPT inlet temperature (T40)
  - HPT exit temperature (T48)
  - LPT exit temperature (T50)
- Tested at 1,251 operating points across operating envelope
  - Maximum power setting
  - Altitude 0 to 40,000 feet
  - Mach number 0 to 0.8
  - Standard ambient temperature to +40°R
  - New to fully deteriorated engine

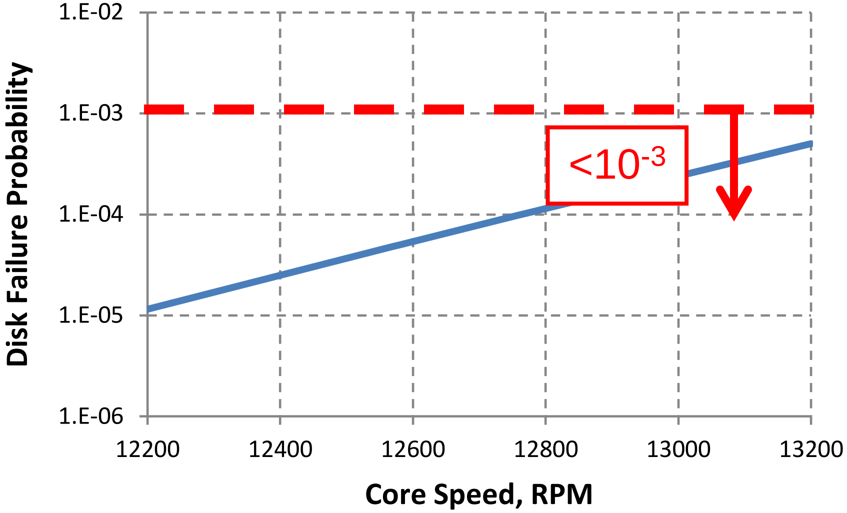


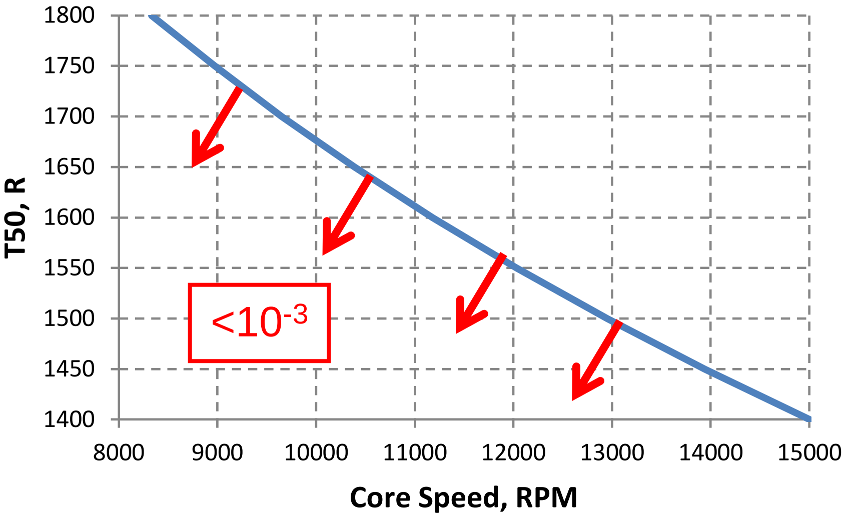


Litt et al., "A Risk Assessment Architecture for Enhanced Engine Operation," AIAA Infotech@Aerospace Conference, 2010.

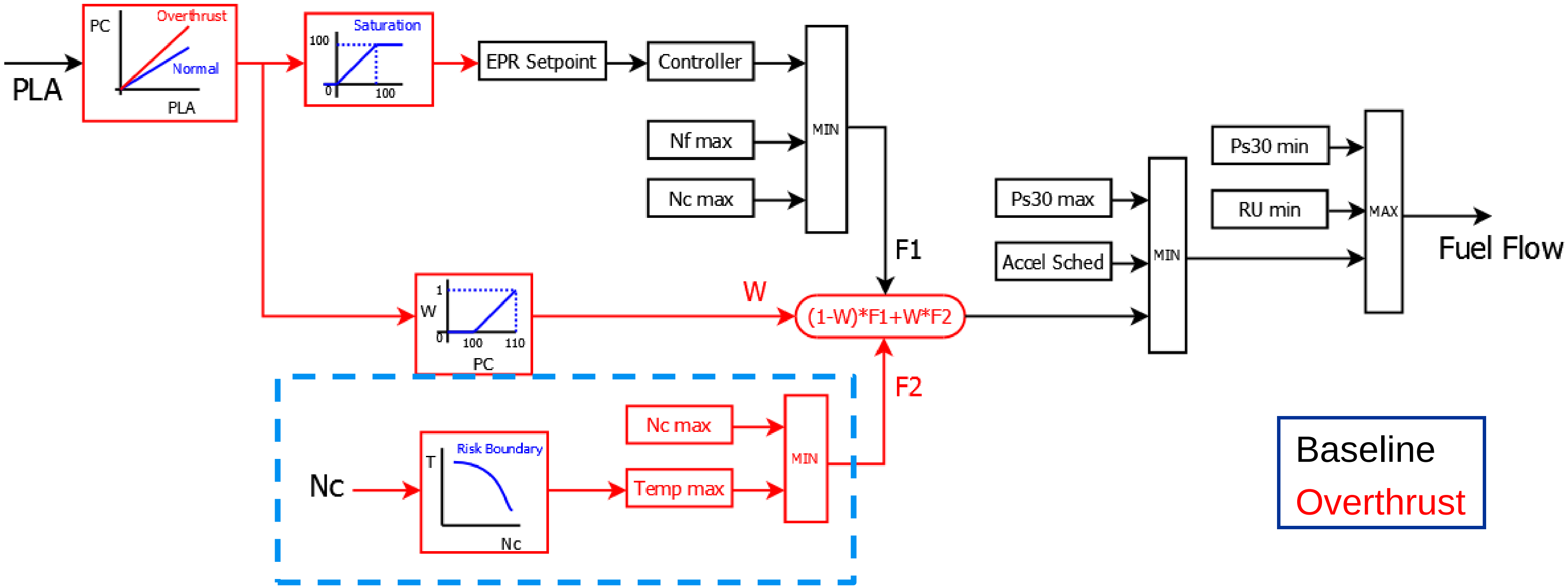
Overthrust: Implementation

- Reduced-order risk function used for control design and implementation (NOT used when evaluating results)
- Disk failure risk as function of core speed
- Blade failure risk as function of core speed and single turbine temperature
- Allowable elevated risk (10^{-3}) manifested as:
  - Core speed limit for disk failure
  - Speed-temperature boundary for blade failure





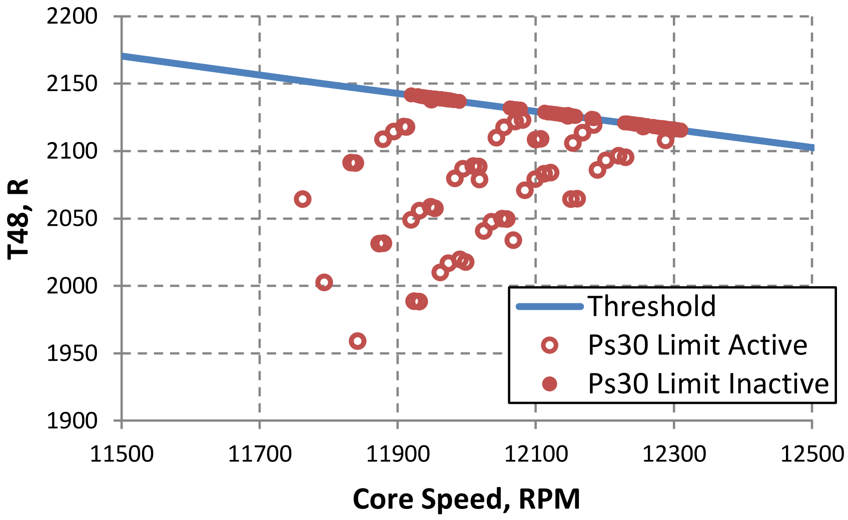
Overthrust: Implementation

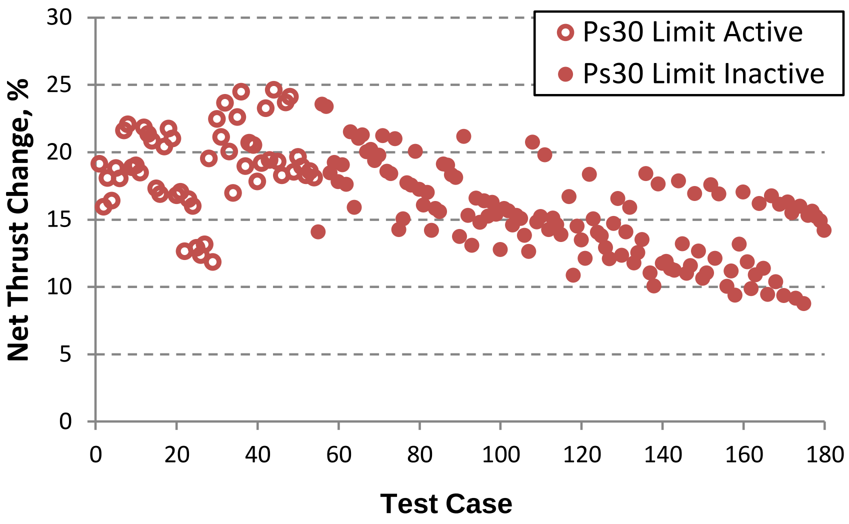


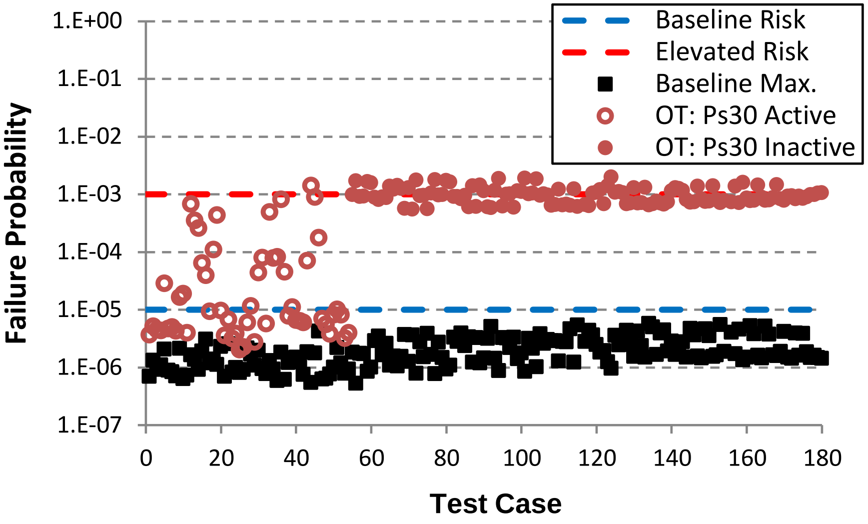
- Core speed and turbine temperature regulators used to maintain engine operating point on risk boundary
- Overthrust activation: PLA mapping switches from idle-to-max to idle-to-overthrust

Overthrust: Results

- Tested at 180 operating points (0 to 4000 feet, Mach 0 to 0.3, standard to +40°R ambient temp, new to full deterioration)
- Maximum power setting: baseline vs. overthrust
- Nc-T48 reduced-order risk boundary (LPT inlet temperature)







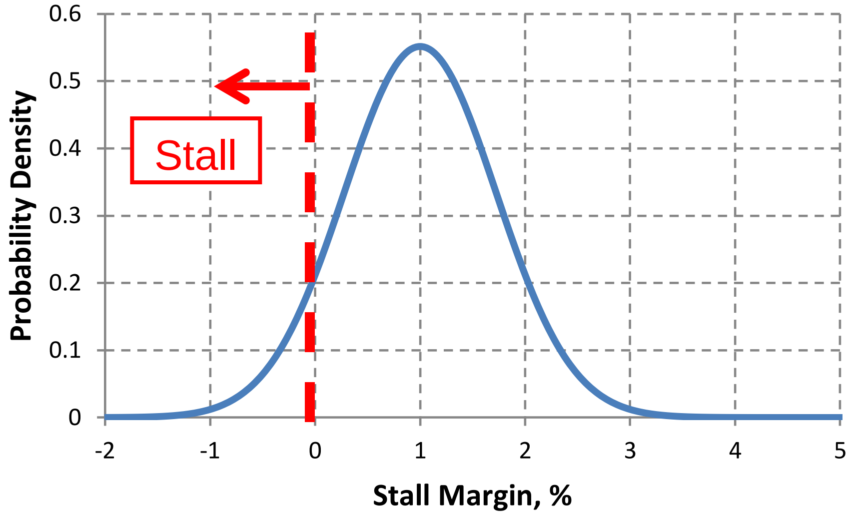
Faster Response: Design Considerations

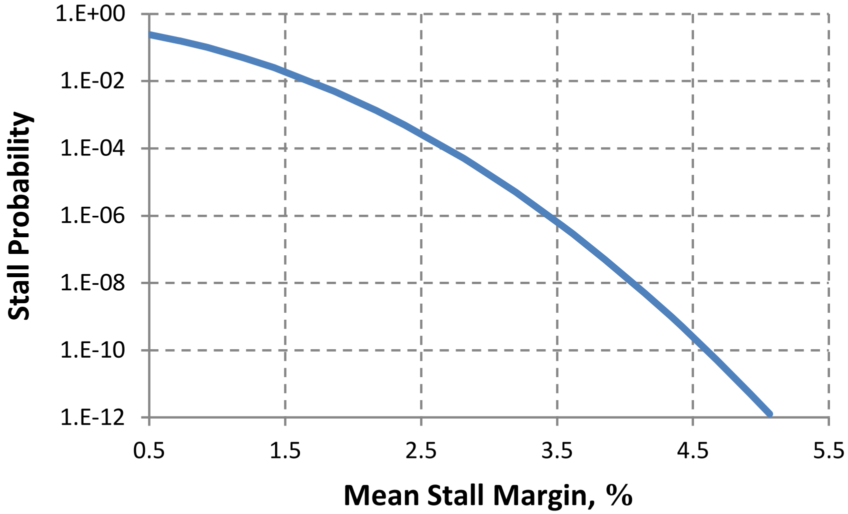
- Reduce time required for idle-to-full power thrust transients
- Risk: high-pressure compressor stall/surge
- No FAA requirement on probability of stall/surge
- Allowable elevated risk level for enhanced performance: 10^{-3}

Faster Response: Risk Function

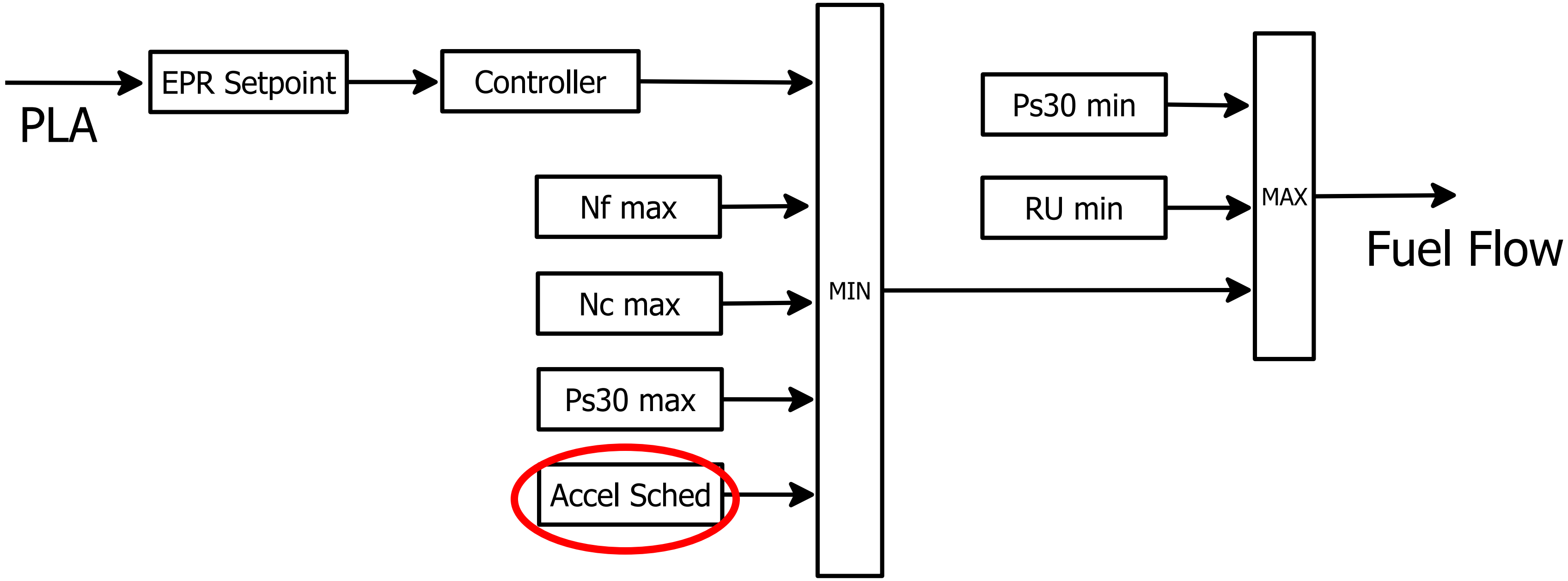
- Statistical stability assessment (SAE AIR1419 Rev. A, 1999)
- Risk of stall modeled as normal distribution
  - Stall margin reported by simulation equals mean
  - Root-sum-square of random effects equals 3 standard deviations
- Stall probability of 10^{-3} corresponds to ~2.3% stall margin

	Destabilizing Effects	Non-random	Random
Operating Line	Inlet Distortion	0.7%	-
	PLA Transient	6.0%	-
	Fuel Control Tolerance	-	±1.15%
	Engine-to-Engine Variation	-	±1.25%
Surge Line	Reynolds Number	0.36%	-
	Inlet Distortion	7.5%	-
	Engine-to-Engine Variation	-	±1.35%
Total		14.56%	2.17%





Faster Response: Implementation

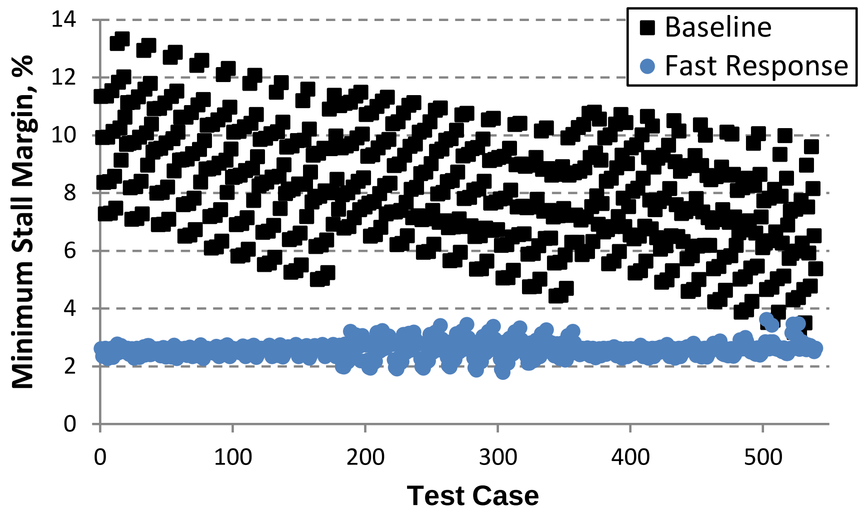


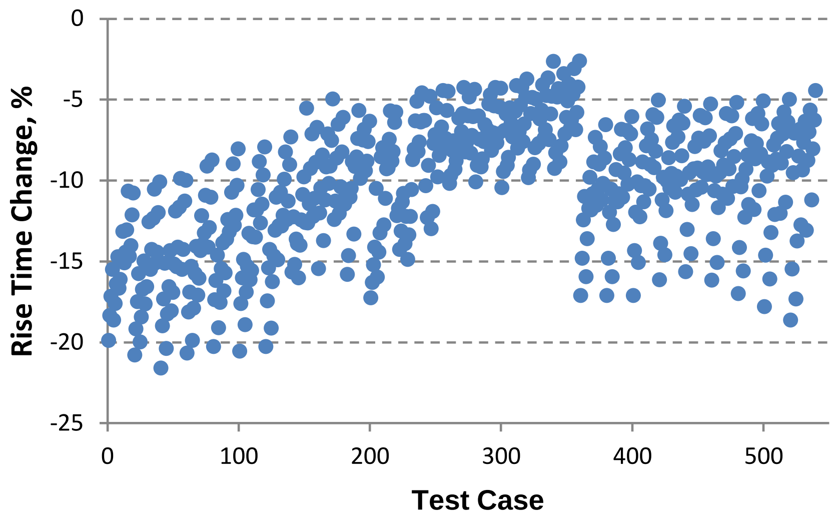
- Shifting acceleration schedule allows for faster dynamic response with lower minimum stall margin
- Iterative search conducted at 60 operating points (0 to 4000 feet, Mach 0 to 0.2, standard to +40°R ambient temperature, new to full deterioration) to determine offset values
- Implementation: 4-D interpolation on operating conditions to determine offset value

- Csank et al., "The Effect of Modified Control Limits on the Performance of a Generic Commercial Aircraft Engine," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2011.
- May et al., "Improving Engine Responsiveness during Approach through High Speed Idle Control," 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 2011.

Faster Response: Results

- Tested at 540 operating points (within interpolation range)
- PLA from flight idle to maximum in 0.1 seconds
- Rise time: time to traverse 10% to 90% of difference between initial and final thrust levels





Summary & Future Work

- Enhanced engine performance based on consistent risk elevation
- Demonstration of implementation on previously introduced enhanced performance concepts
- Characterization of engine failure/malfunction risk
- Ongoing & future work:
  - Implementation and pilot testing in flight simulator
  - Faster response mode with stall margin estimation